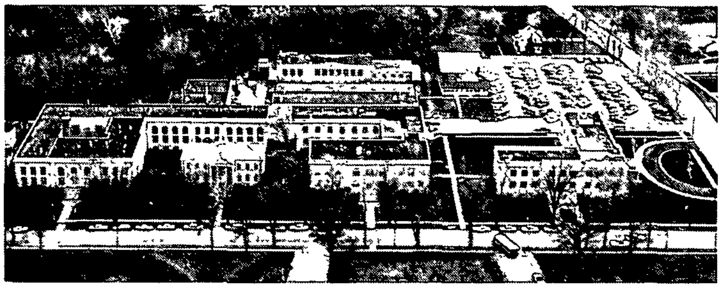

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AN INVESTIGATION OF DROPLET SIZE DISTRIBUTION FROM COMMERCIAL KRAFT BLACK LIQUOR SPRAY NOZZLES

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AN INVESTIGATION OF DROPLET SIZE DISTRIBUTIONS FROM COMMERCIAL KRAFT BLACK LIQUOR SPRAY NOZZLES

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ABSTRACT

Model fluid tests were performed at the Weyerhaeuser Company to compare the performance of traditional black liquor spray nozzles against several spray systems which might offer improved droplet size distributions. While some improvements were indicated, totally reliable results were seen to require improved spray imaging.

In subsequent experiments at The Institute of Paper Chemistry, flash x-ray radiography has demonstrated the ability to more clearly image these large complex sprays. Preliminary results with concentrated black liquor are presented. Current activities, including the construction of a dedicated black liquor spray test facility, are discussed.

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INTRODUCTION

Black liquor spray droplet size distribution is one of the most critical operating variables to control for optimal kraft recovery boiler operation. Unlike most combustion processes, black liquor burning requires a relatively large average droplet size. Droplets with initial diameters less than approximately 1.0 mm exhibit increased burning rate, particle swelling and sulfur emissions. These effects combine to foul heat transfer surfaces with both excessive carryover and difficult to remove fume deposits. Droplets which are too large may reach the char bed wet, causing furnace instabilities and blackouts. Thus there appears to be some optimal droplet size in the 2-4 mm range.

Recovery boiler spray nozzles are unique among fuel delivery systems both in terms of droplet size and flow rate. Desired operation more closely resembles that for spray drying. Some typical operating parameters are listed in Table 1. Black liquor sprays are also very large in terms of coverage, with a common nozzle producing a flat spray several meters across. All of these factors explain the lack of quantitative data on commercial black liquor spray nozzle performance.

Table 1 here

This paper describes two related efforts to better quantify the performance of these large spraying systems. The first involves model fluid tests performed at the Weyerhaeuser Company during 1981-1982, while the second is an ongoing project at The Institute of Paper Chemistry which involves the spraying of concentrated kraft black liquor at typical operating conditions. The former study utilized optical imaging techniques, while the latter is making use of flash x-ray imaging (FXR).

STUDIES AT THE WEYERHAEUSER COMPANY

Objectives of these studies were twofold. Quantification of commercial spray nozzle performance (droplet size distribution) with model fluids was the first objective. The second was to determine if other common pressure nozzles offered improved performance.

Glycerine-water mixtures were employed as model liquids to simulate black liquor. Liquid viscosities ranged from 0.001-0.2 Pa.s.

The experimental setup is shown in Fig. 1. Most of the data were obtained from high speed (10000 fps) movies, while some came from still photographs. Data reduction was performed with a Quantemet 200 image analysis system. Some results for a Babcock & Wilcox splash plate nozzle are shown in Fig. 2. Figure 3 depicts results for a Combustion Engineering hollow cone nozzle. Several other commercially available pressure nozzles were investigated and some of these results are shown in Fig. 4 and 5.

Figures 1-5 here

It is difficult to compare the performance of these nozzles, as the average droplet sizes vary. Some measure of comparison was obtained by assuming that each distribution was log-normal and maintained constant geometric standard deviation over a range of average droplet sizes. With these assumptions one can estimate nozzle performance at some new average droplet size away from that of the actual experiment. Figure 6 depicts the result of this exercise and shows that several nozzles should perform better than those currently in use when operated at a constant average droplet size of 3.0 mm. One must be careful here, as the degree of extrapolation (and hence accuracy) varies among the nozzles. Some may be out of the practical range of operation.

Figure 6 here

The following observations and conclusions were reached from the Weyerhaeuser studies:

1) All tests produced smaller droplet size distributions than expected.
2) The large range of droplet size and the large area of coverage of these sprays cause many problems for optical imaging techniques which have been used in the study of more traditional (smaller) spray devices. Specific problems include resolution, depth of field and overall field of view required to obtain statistically significant results.
3) There was some evidence that alternative pressure nozzles may produce narrower droplet size distributions than current nozzles. The Delavan "Raindrop" nozzle showed some promise, as it was used commercially to eliminate the fine droplets from pesticide spraying operations.

RESULTS OF BENNINGTON AND KEREKES

In 1986, Bennington and Kerekes[1] presented results of concentrated black liquor spray tests which have many implications for future work in the area. In this work, water, glycerine-water mixtures and concentrated black liquor were sprayed from relatively small pressure nozzles. The experimental conditions are listed in Table 2. Conditions b and c are of significance. Although the liquids were of the same viscosity, droplets obtained from black liquor were approximately twice as large as those from the model fluid.

Table 2 here

Lapple *et al.*[2] have combined much of the data obtained for droplet size distributions from grooved core nozzles such as those used in the Bennington study and have found reasonable correlation with Eq. (1).

$$d = K\, D^{1+a+b}\, U^{a+2b}\, \rho^{a+b}\, \mu^{-a}\, \sigma^{-b} \qquad (1)$$

where :	d	=	mean droplet size (m)
	K	=	5.5
	D	=	nozzle orifice diameter (m)
	U	=	superficial liquid velocity (m/s)
	ρ	=	liquid density (kg/m^3)
	μ	=	liquid viscosity (Pa.s)
	σ	=	liquid surface tension (N/m)
	a	=	-0.20
	b	=	-0.24

For the glycerine-water mixtures used by Bennington ρ = 1164 kg/m^3, μ = 0.0147 Pa.s and σ = 0.067-0.069N/m. The black liquor viscosity was measured as 0.015 Pa.s. The density of 55% solids liquor at this temperature is approximately[3] 1300 kg/m^3. Krishnagopalan[4] has measured the surface tension of concentrated black liquors at elevated temperatures and obtained values near 0.03N/m for 55% liquor at 100°C. By using these parameters and Eq. (1) an increase in droplet diameter of 15% would be predicted when changing from the glycerine water mixture to black liquor.

While Eq. (1) is quite empirical and often qualitative, one conclusion is inescapable. The differences between model liquid and concentrated black liquor droplet size distributions cannot be attributed to simple differences in physical properties such as surface tension. Nearly all predictive correlations for droplet size employ values for b between -0.1 and -0.5 and would thus rule out surface tension as the cause.

The results of previous work at Weyerhaeuser and those of Bennington clearly indicate that model liquids (at least glycerine-water mixtures) should not be used to simulate concentrated black liquor if results are to apply to actual spraying and combustion processes.

FLASH X-RAY RADIOGRAPHY (FXR) STUDIES AT IPC

Work done at Weyerhaeuser and by Bennington and Kerekes indicate that a very different approach must be taken for studying and, in particular, imaging black liquor sprays. Both of the previous studies were lacking in the sense that they sampled only a small fraction of the large overall spray. The Weyerhaeuser studies identified several shortcomings of traditional optical imaging when investigating these sprays. Bennington showed that results applicable to black liquor can only be obtained through studies of actual black liquors at elevated temperatures. Clearly, these requirements can only further exacerbate the problems observed during model fluid tests. Therefore a need exists to develop some technique capable of imaging commercial black liquor sprays at typical operating conditions.

Recent work at IPC has applied the technique of FXR to the problem of imaging high speed multiphase flows which are difficult to study optically.[5] Several excellent texts[6-8] describe FXR in detail. Briefly, all FXR systems comprise three components:

- A pulsed power supply
- An x-ray generator
- Some x-ray detector

FXR power supplies usually take the form of Marx-Surge generators or pulse transformers. The former typically deliver 30-70 nanosecond pulses in the 0.15 to 2.5 MeV range at current levels on the order of 10^4 A. While pulse transformers operate at the lower end of this range, they do offer the possibility of high repetition rates (10^4 pulses per second) while M-S generators are essentially single flash devices.

All practical x-ray generators currently in use are of the field emission type. A common design is shown in Fig. 7. Under sufficiently high applied voltages (10^7-10^8 V/cm) electrons leave the cathode and bombard the anode, resulting in the emission of a short burst of Bremsspectrum x-rays. FXR system resolution is essentially determined by source size and geometrical arrangement as shown in Fig. 8.

Figures 7 and 8 here

High speed industrial x-ray films are the least expensive and highest resolution x-ray detectors available. Fluorescent screens and image intensifiers can be used to improve sensitivity (penetration), but resolution is lost in both cases.

Several FXR systems are listed in Table 3. Those highlighted with an asterisk are part of a unique FXR laboratory at The Institute of Paper Chemistry.

Table 3 here

FXR possesses several advantages relative to optical imaging, especially in the case of black liquor spray imaging. Speed is not an issue as all FXR system exposure times are in the 30-100 ns range. FXR produces a simple shadowgraph (actually a density map) so there is no real "depth of field" concern. Gray levels in the resulting radiograph can be easily correlated with mass present. Since it is essentially a mass measurement, the presence of large quantities of steam at elevated firing temperatures is of no concern. Most significantly, FXR can easily image a 1 x 1 m area with 100 μ resolution throughout the field of view. While FXR has been traditionally used in the weapons laboratories to image ballistic events, one application to small sprays has been found.[9]

Figures 9 and 10 are FXR images of concentrated black liquor sprays obtained at the conditions shown in Table 4. These radiographs were taken with a 150 kVp FXR system with 70 ns exposure time (Hewlett-Packard model 43731A). FXR is unique in its ability to see through the complex spray (even close to the nozzle) and clearly shows the simultaneous occurrence of sheets, filaments and droplets.

Figures 9 and 10 and Table 4 here

CONCLUSIONS AND DISCUSSION

Studies performed at the Weyerhaeuser Company and by Bennington and Kerekes demonstrate the need for some imaging technique which will allow the study of large, commercial black liquor sprays at elevated temperatures. In very preliminary tests, FXR has shown a unique ability to image these complex sprays.

One problem requires attention. The finite size of any practical FXR source causes some image blur. This can be reduced by maximizing the source to film distance. The problem may also be eliminated through the use of special microfocus x-ray tubes or via digital image processing.

At this time a unique facility is under construction to allow the systematic investigation of large black liquor sprays via FXR. Early studies will include the effects of black liquor concentration, temperature and flowrate on droplet size distribution from current spray nozzles.

ACKNOWLEDGMENTS

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REFERENCES

1. Bennington, C. P. J. and Kerekes, R. J., Journal of Pulp and Paper Science 12(6):J181-J186(1986).
2. Lapple, C. E. et al. "Atomization - A survey and critique of the literature." Stanford Research Institute, Menlo Park, CA, 1967.
3. Fricke, A. L. Physical Properties of Kraft Black Liquor Interim Report-Phase II, DOE contract No. AC02-82CE40606, 1985.
4. Krishnagopalan, J., Ph.D. Thesis, Department of Chemical Engineering, University of Maine, 1986.
5. Farrington, T. E., Proceedings of TAPPI Engineering Conference, Seattle, 1986.
6. Frungel, F. B. High speed pulse technology, Vol. III, Academic Press, 1976.

7. Jamet, F. and Thomer, G. Flash radiography, Elsevier Publishing Company, 1976.

8. Charbonnier, F. The nondestructive testing handbook on radiography and radiation testing - Section 11 - Flash radiography, ASNT, 1983.

9. Bahl, K. L. and Vantine, H. C., Proceedings of 1976 Flash Radiography Symposium, ASNT:193-200(1977).

Table 1. Desired Spray Characteristics.

	Black Liquor	Fuel Oil	Spray Drying
Average droplet diameter, mm	2-4	0.01-0.05	0.01-1.0
Flowrate ($m^3/s \times 100^3$)	1-8	0.1-1	1-10

Table 2. Conditions for Bennington Test.*

Experiment	a	b	c
Liquid	Water	64.8% glycerine/ water	55% black liquor
Temperature (°C)	18	23	120
Viscosity (Pa.s)	0.001	0.0147	0.015

*Tests performed with Spraying Systems Grooved Core Nozzle (1/4 LNN2).

Table 3. FXR Systems.

	Builder	Exposure Time (s)	Framing Rate (fps)	X-ray Spot Size (mm)	Energy (KeV)
1.	*Hewlett-Packard	3×10^{-8}	0	5	300
2.	*Hewlett-Packard	7×10^{-8}	0	1	150
3.	*Lawrence Livermore Laboratory	3×10^{-8}	0	< 0.1	150
4.	Impulsphysics (GMBH)	10×10^{-8}	5×10^{3}	1	150

Table 4. Black Liquor Test Conditions.

FXR System - Hewlett-Packard 150 kVp
Film - Kodak AR-5
Spray Nozzle - B&W #17 Splash Plate

	Figure 9	Figure 10
Source to film distance (m)	0.53	0.53
Black liquor concentration (%)	65	65
Black liquor temperature (°C)	104	111
Black liquor pressure (kPa)	238	185

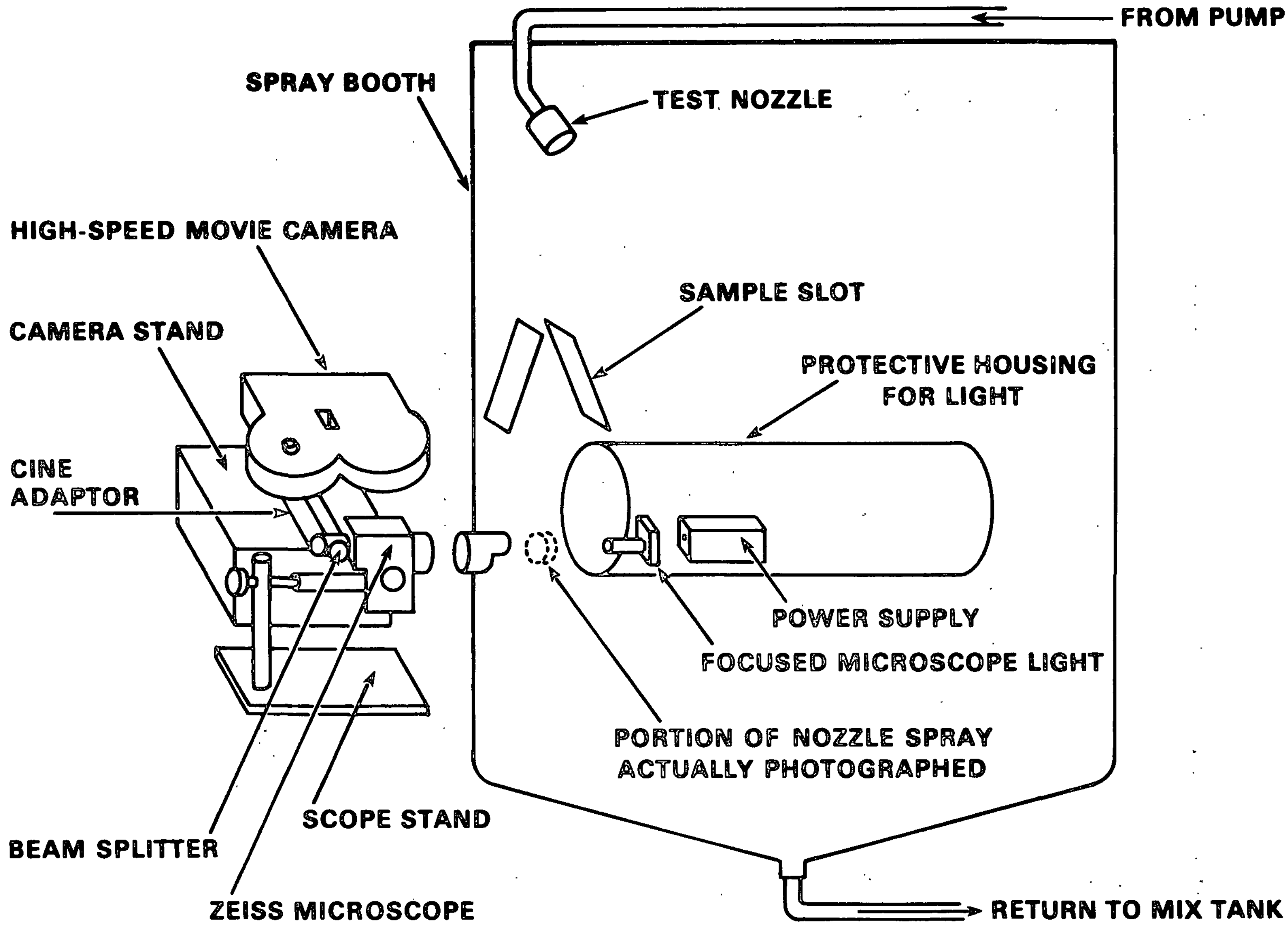

Figure 1. Experimental Setup for Weyerhaeuser Tests.

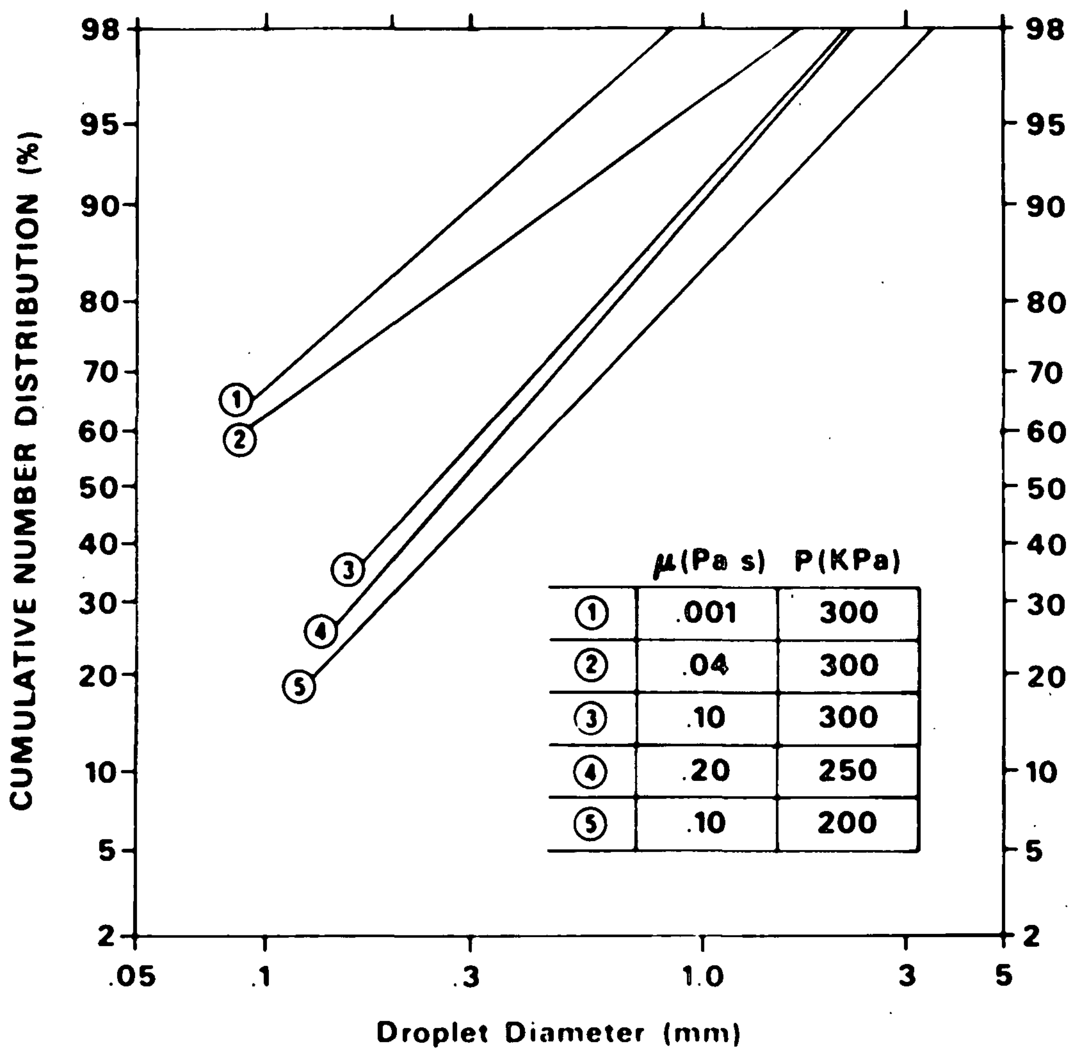

Figure 2. Droplet Size Distribution - Babcock & Wilcox #15-52 Splash Plate Nozzle.

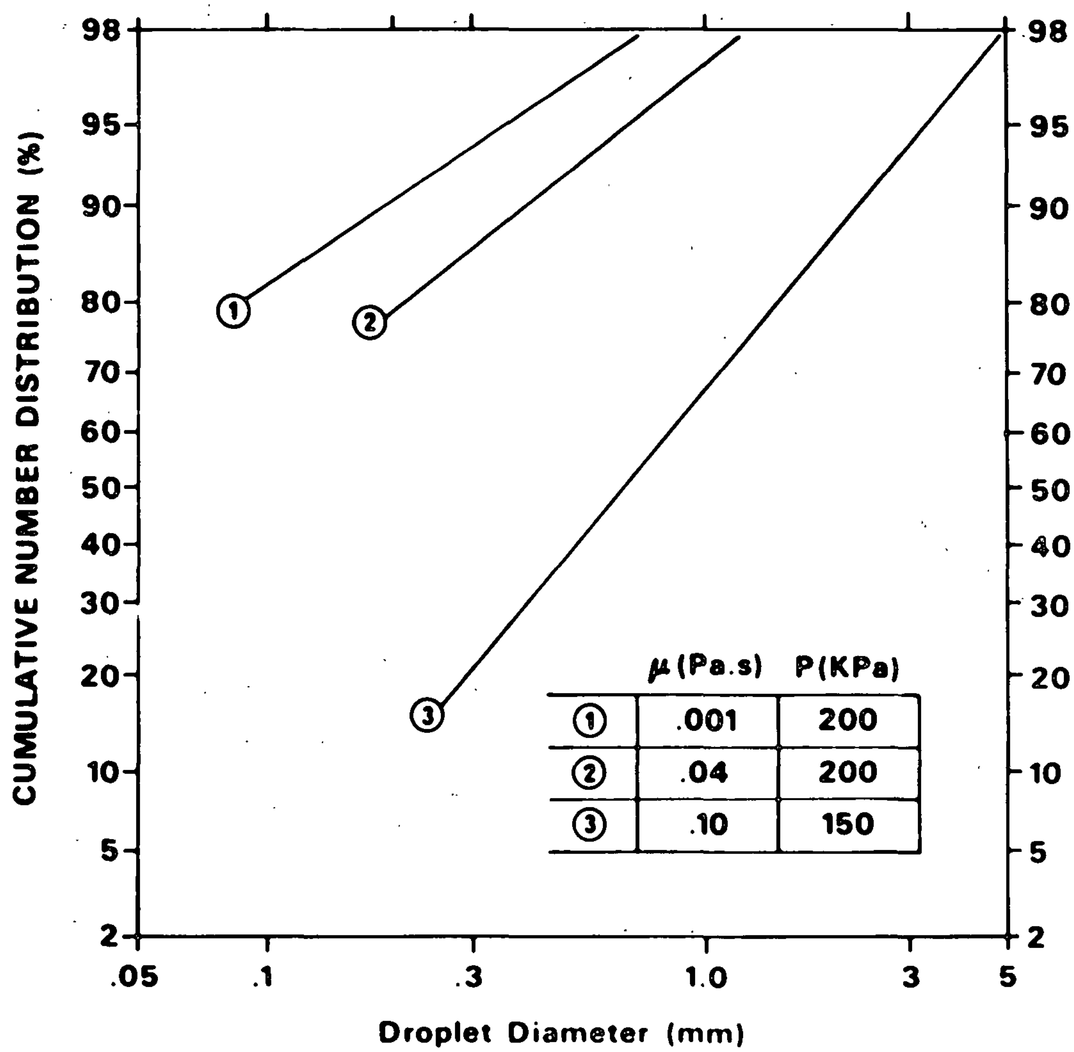

Figure 3. Droplet Size Distribution - Combustion Engineering Swirl Insert Nozzle.

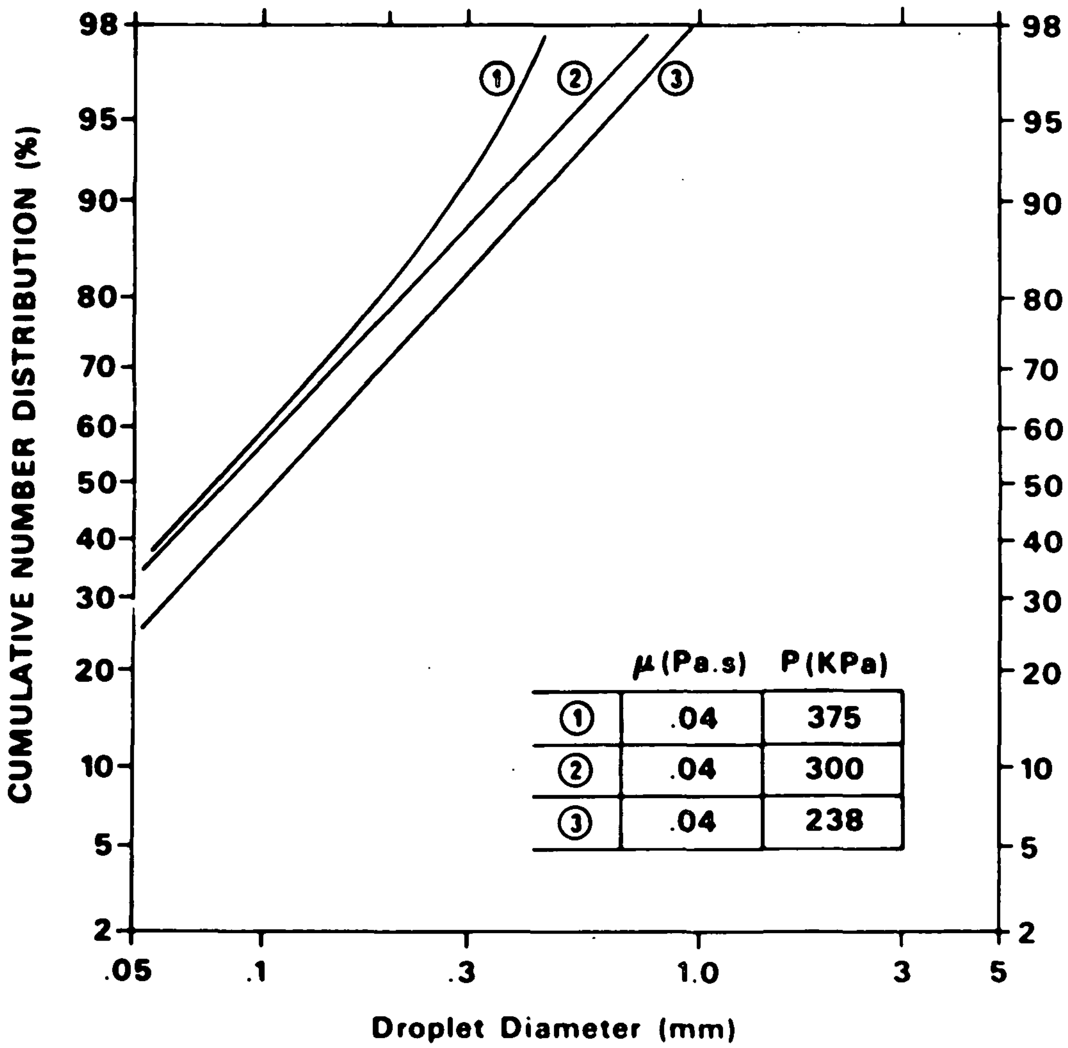

Figure 4. Droplet Size Distribution - Spraying Systems Hollow Cone #62341323.

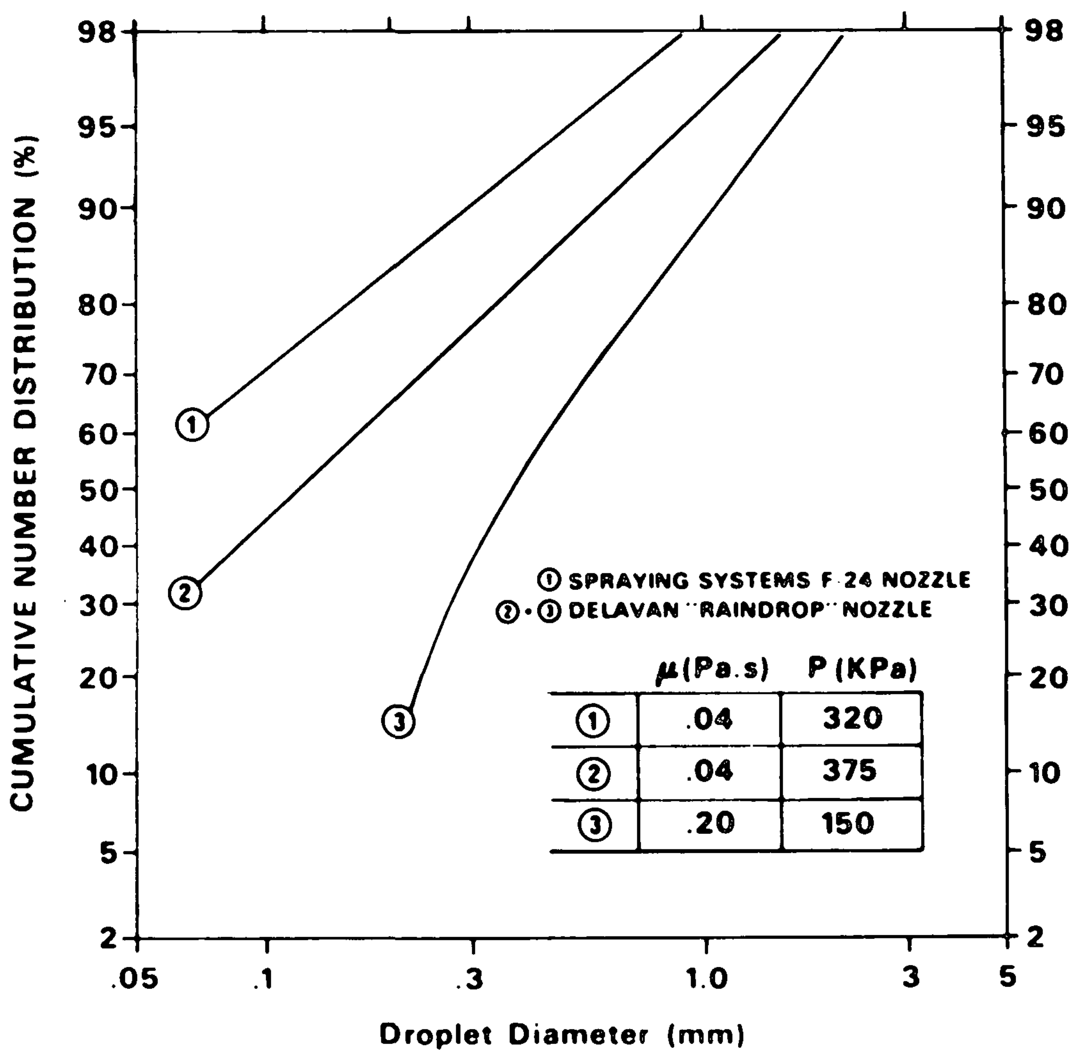

Figure 5. Droplet Size Distribution - Several Other Commercial Pressure Nozzles.

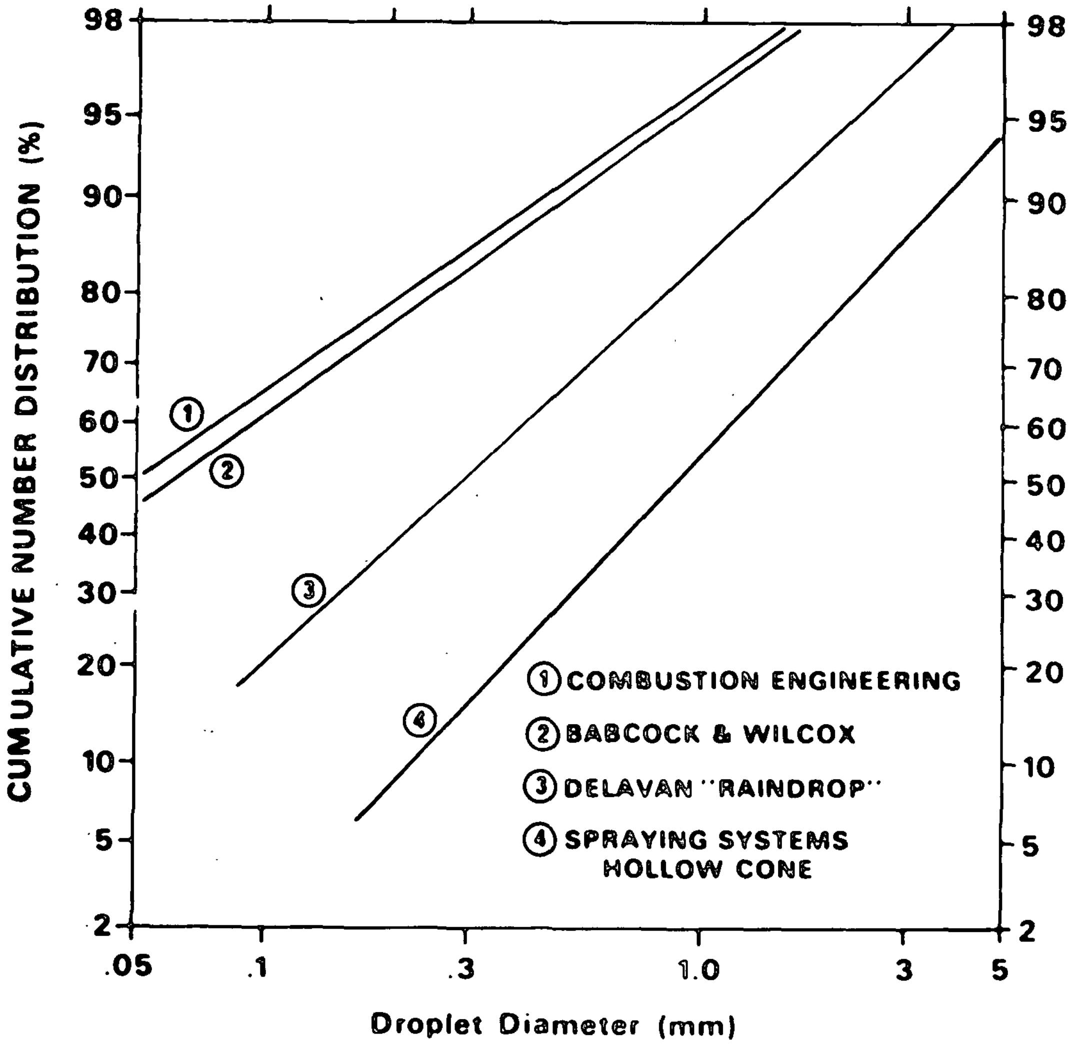

Figure 6. Theoretical Performance at D_{VM} = 3.0 mm.

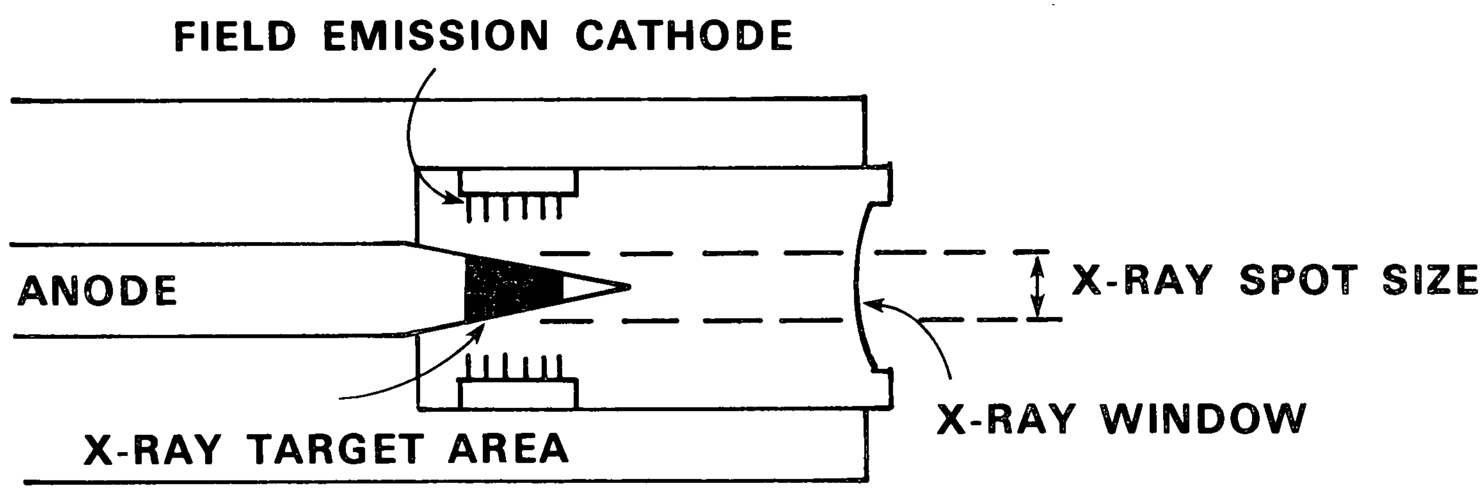

Figure 7. Common X-ray Generator for FXR.

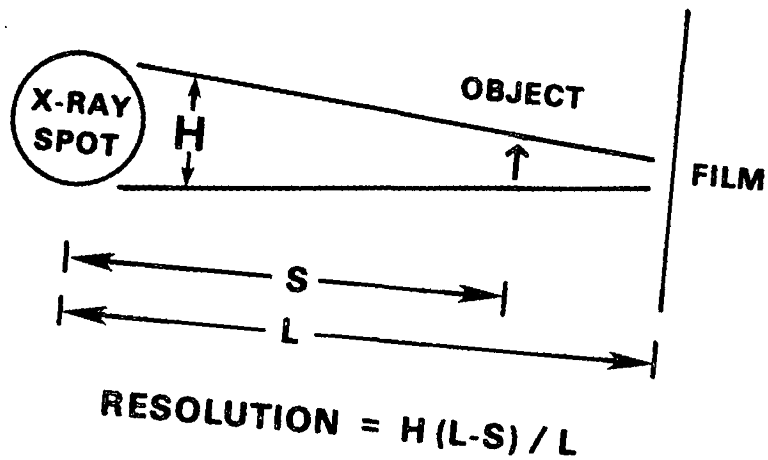

Figure 8. FXR Resolution.

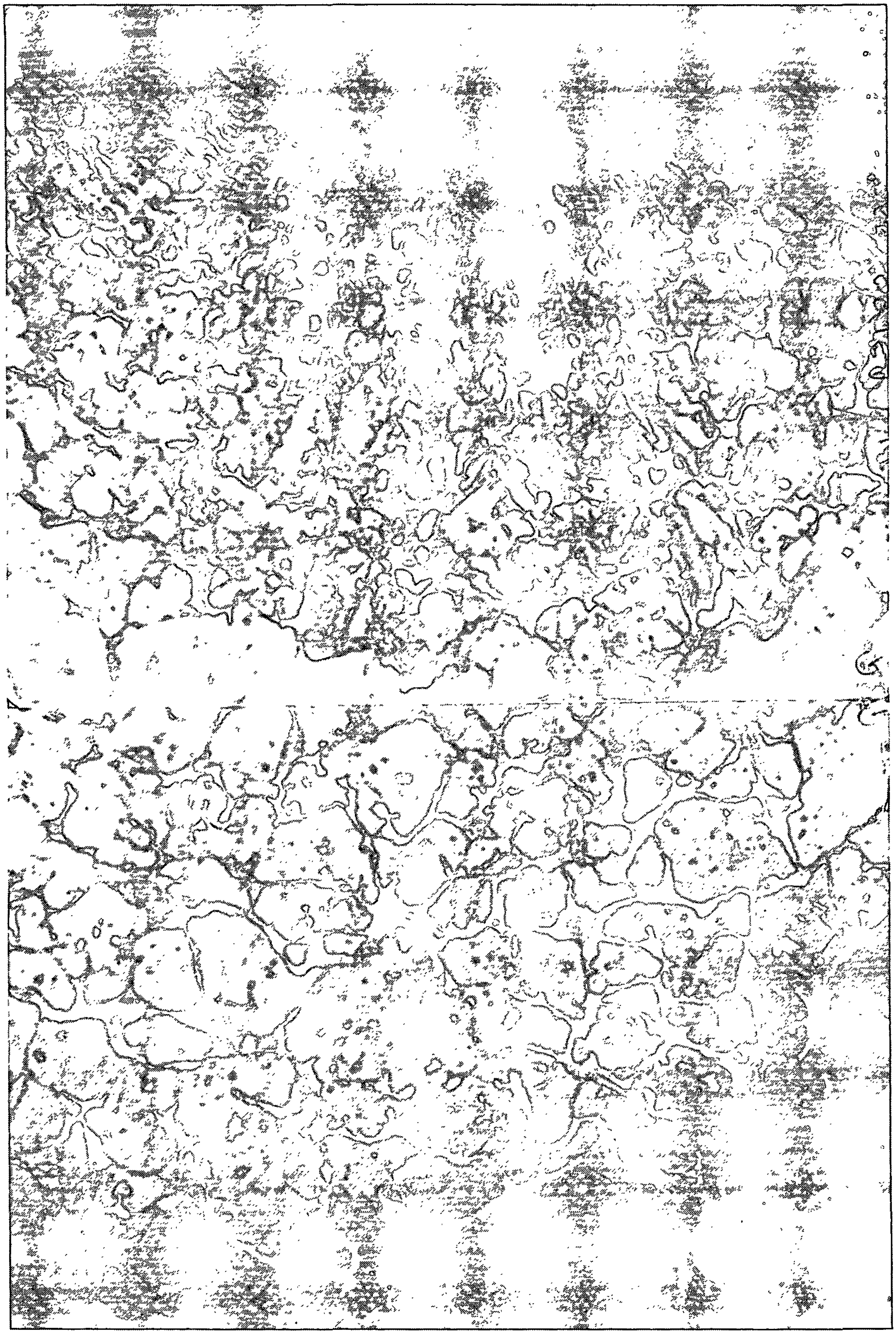

Figure 9. FXR Image of Concentrated Black Liquor Spray.

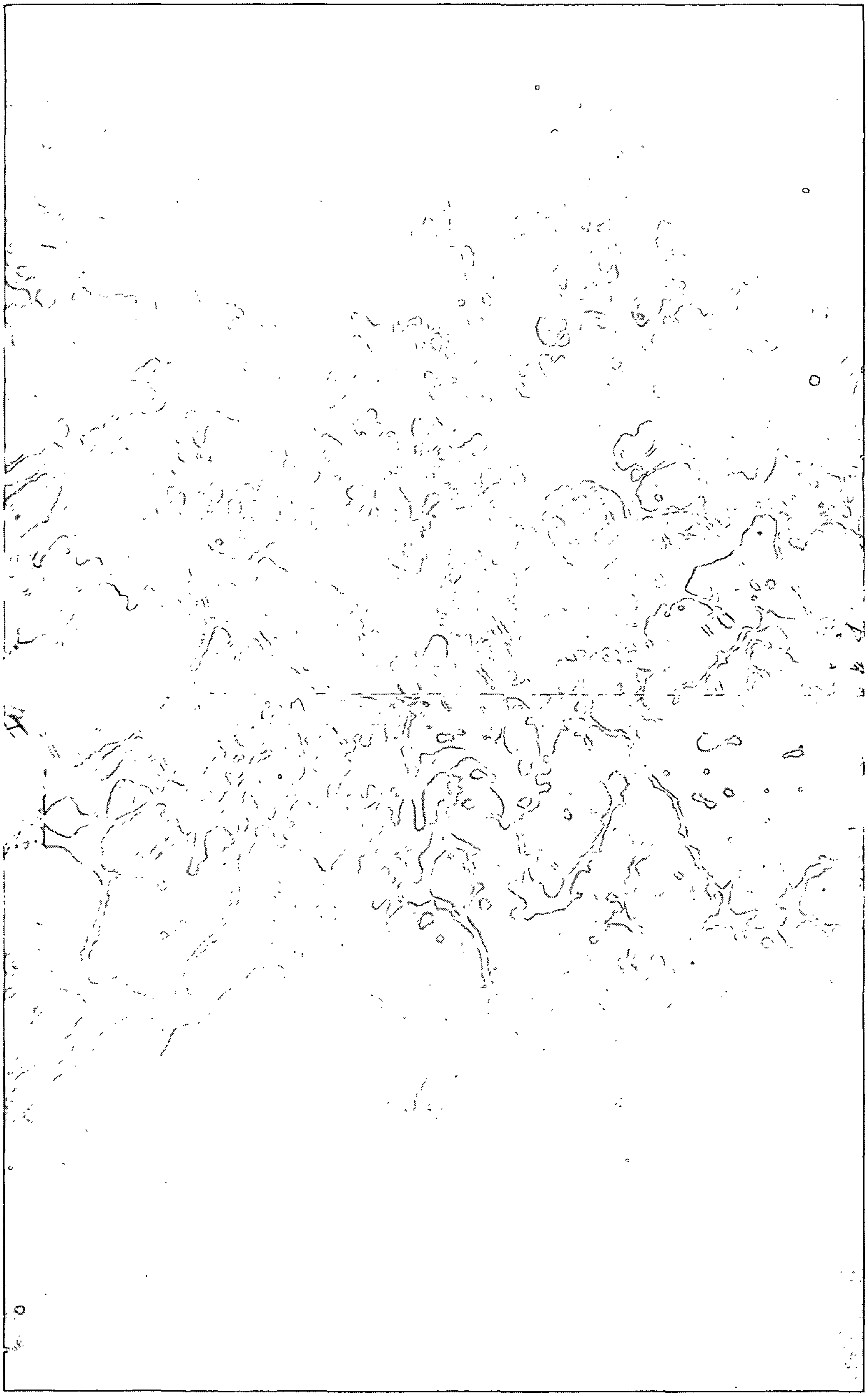

Figure 10. FXR Image of Concentrated Black Liquor Spray.